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# Liquid-Desiccant Vapor Separation Reduces the Energy Requirements of Atmospheric Moisture Harvesting

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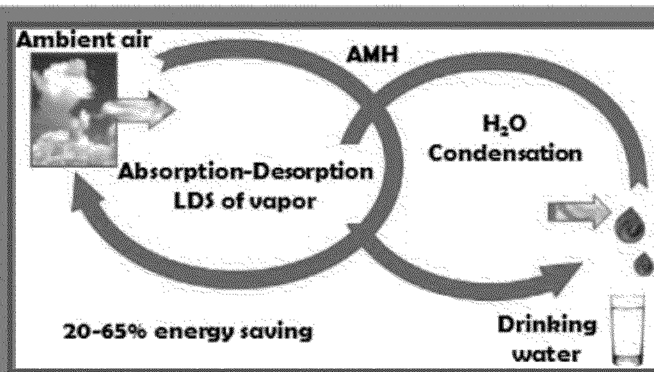
* Supporting Information

An innovative atmospheric moisture harvesting system is proposed, where water vapor is separated from the air prior to cooling and condensation. The system was studied using a model that simulates its three interconnected cycles (air, desiccant, and water) over a range of ambient conditions, and optimal configurations are reported for different operation conditions. Model results were compared to specifications of commercial atmospheric moisture harvesting systems and found to represent saving of 5−65% of the electrical energy requirements due to the vapor separation process. We show that the liquid desiccant separation stage that is integrated into atmospheric moisture harvesting systems can work under a wide range of environmental conditions using low grade or solar heating as a supplementary energy source, and that the performance of the combined system is superior.




## INTRODUCTION

The ever growing world population and the increasing demand for freshwater is overstretching the natural water resources in many arid and semiarid regions around the globe.[1] As existing potable water resources are being depleted, alternative water sources and innovative technologies for drinking water production are sought. Desalination of seawater by reverse osmosis (RO) has become cost-effective in the past decade[2] and is among the most promising technologies for intensive freshwater production. However, it requires a large saline water source and therefore is not applicable in countries or regions that do not have access to the sea or to underground saline water reservoirs. Moreover, desalination requires large capital investments for building the desalination plant. Supplying water to noncoastal and inner regions requires, in addition, significant capital investment in piping and pumping infrastructure, and in its operation and maintenance. Such an investment may be cost prohibitive, especially when the water should be delivered to scattered populations. Atmospheric moisture is another potential source of freshwater, which sums up to a significant amount and is accessible essentially everywhere. The atmosphere contains about 13 000 $km^3$ of freshwater, 98% of which are vapor and only 2% are in a condensed phase (clouds, fog). In fact, this amount is comparable to all the surface and underground freshwater (excluding ice and glaciers).[3] Fog can be simply collected from the air merely by impaction and interception of the fog droplets on collection surfaces.[4] Indeed, fog harvesting has been practiced and studied considerably over the last few decades.[5] Recent studies are focused on optimizing the surface properties of fiber network structures[6] for increasing the harvesting potential.[4,7] However, the limiting factor of fog harvesting is the global unavailability of the necessary meteorological conditions that support frequent fog occurrence. Specifically, several environmental processes can cause the temperature of moist air to drop below its saturation temperature and form fog. Yet, the occurrence of such processes characterizes only limited number of places that enjoy favorable conditions. Thus, on a global scale, fog is even less accessible than seawater as an alternative source of freshwater.

Water vapor is prevalent in the atmosphere but its harvesting is more thermodynamically complicated than fog harvesting since the vapor must be condensed to liquid water - a process that involves significant release of heat (~2500 $kJ/kg_w$). Condensation occurs when moist air is cooled to a temperature below its dew point, normally in close proximity to cold surfaces whose properties promote the formation of liquid droplets.[8] The surface temperature has to remain below the ambient dew point temperature for condensation to continue despite the release of the latent heat of condensation and the sensible heat interactions of both the condensing and the noncondensable components of the ambient air. Naturally, dew is formed when the surface temperature is maintained below the dew point temperature as a result of radiative cooling of the surface toward the night sky, which acts as a heat sink.[9] As such, dew formation is limited by the surface radiation properties, and is highly affected by the ambient conditions.[10] Indeed,

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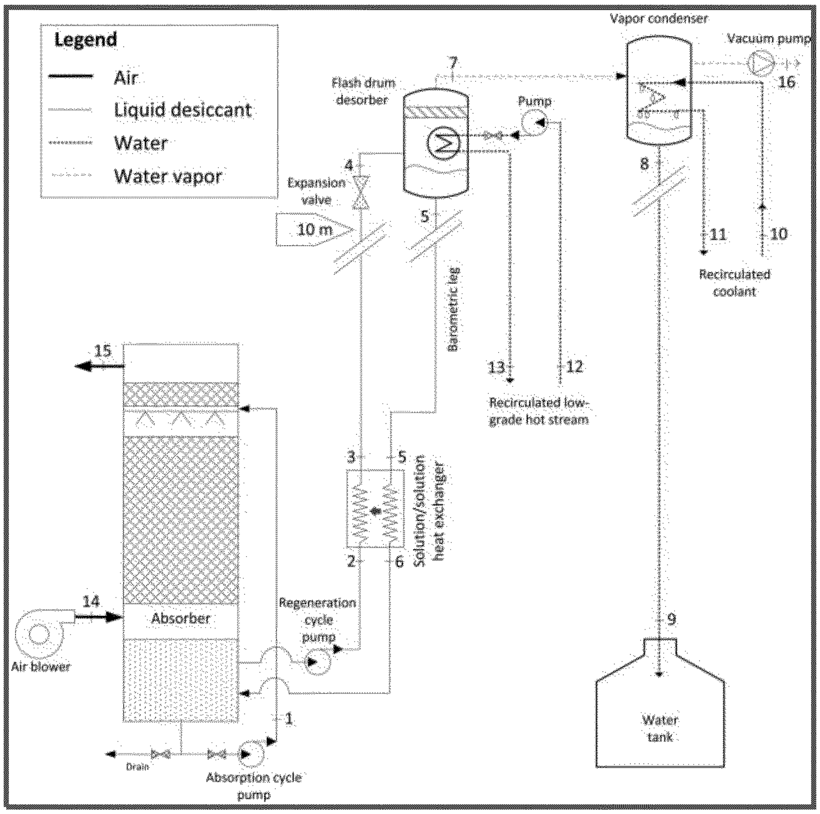


Figure 1. Schematic design of the liquid desiccant vapor separation system. Numbers indicate locations where the thermodynamic state is calculated by the model.

passive dew collection was argued to yield ~0.8 mm $H_2O$/night[11] but empirical data suggest lower yields.[12−14] Still, in coastal areas with high relative humidity passive dew collection may be a supplementary water source.[15,16] However, when the dew point temperature is significantly lower than the ambient temperature a very significant sensible heat interaction between the air and the surface takes place. This sensible heat interaction poses further demands on the surface radiative cooling and may prevent it from reaching or maintaining the dew point temperature, thus diminishing dew condensation. Thus, the dew yield is very sensitive to the ambient conditions and nights with zero yield are common even in sites with generally favorable meteorological conditions.

Alternatively, active atmospheric moisture harvesting (AMH), where the heat interactions (latent and sensible) involved in the process are handled by, e.g., a standard electrical compression−expansion refrigeration unit,[17,18] can ensure continual water production for varying ambient conditions. However, relative to RO desalination the specific (per one $kg_w$ of water production) energy requirement of such an AMH system is about 2 orders of magnitude higher,[18] with the piggyback sensible heat interaction of the air consuming 40−90% of the energy, depending on ambient conditions. This suggests that a significant reduction in the energy requirements may be achieved if the vapor is separated from the air bulk before it enters the condenser, such that only the vapor is cooled rather than the entire air bulk. In fact, a selective membrane technology has been suggested for this purpose,[19] with the performance of the whole membrane-assisted humidity harvesting system evaluated numerically for limited ambient conditions and showing energy saving of up to 50%. However, the very large membrane area requirement commands the development of high-performance membrane modules (and of hermetically sealed low-power fans), which are not yet commercially available. Hence, implementation of this technology is not currently feasible. An alternative approach for separating water vapor from the air is by using a desiccant. In this work, an active method of liquid desiccant-assisted atmospheric moisture harvesting is proposed for producing large amounts of drinking water, and its energy requirements are compared to those of common electromechanical AMH systems. Specifically, we describe the design and numerically examine the performance of a continuous liquid-desiccant vapor separation AMH system, and compare the LDS-AMH performance over a wide range of environmental conditions with that of direct cooling AMH systems, which are the benchmark technology for active AMH.

## ATMOSPHERIC MOISTURE HARVESTING

Few commercial direct cooling AMH systems exist in the market. AMH by direct cooling involves contact of the ambient air with a cold surface, with the temperature difference facilitating heat transfer from the air to the surface, resulting in cooling of the air. The humidity that exceeds the vapor saturation capacity of the chilled air condenses on the surface. The total heat interaction of the air is the sum of the sensible heat interaction, which is associated with the temperature change of the air and the vapor, and the latent heat release, which is associated with the enthalpy of condensation,[20]

$$q_{tot} = q_s + q_l \tag{1}$$

where $q_{tot}$ [kJ/$kg_a$] is the total heat interaction, $q_s$ [kJ/$kg_a$] is the sensible heat interaction, and $q_l$ [kJ/$kg_a$] is the latent heat of condensation. Since the mass of dry air is constant throughout



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the process, all the interactions are defined per one kg of dry air (denoted by $kg_a$).

In a previous work,[18] we examined the ratio of the latent-to-total heat interactions and designated it the Moisture Harvesting Index (MHI). We showed that the MHI is a key parameter for assessing the overall energy requirements of an AMH process. A global survey revealed that in areas most suitable for AMH, e.g., tropical regions, about half of the total heat interaction of a direct cooling AMH system is due to sensible heat removal. In dryer regions, the sensible heat interaction may amount to about 90% of the total heat interaction. This suggests that separating the vapor from the bulk air prior to cooling may reduce significantly the energy demands of an AMH system.

## LIQUID-DESICCANT VAPOR SEPARATION

The proposed liquid-desiccant vapor separation (LDS) subsystem was designed to operate continuously in a closed-cycle, and its regeneration requires low-grade or solar heat. The product of this subsystem is pure water vapor, which is then condensed by a standard refrigeration system without the burden of cooling the air. The system consists of six major components (Figure 1): a vapor absorber (dehumidifier), a liquid−liquid heat exchanger, a flash-drum vapor desorber that also regenerates the liquid desiccant solution, a condenser, and two barometric legs.

The absorber is simulated as an adiabatic packed-bed tower filled with a high surface area packing material on which a desiccant solution of $LiCl_{aq}$ (state 1) trickles, however other designs are possible, e.g., an internally cooled absorber.[21] Ambient air (state 14) enters the absorber and contacts the concentrated desiccant solution, with the vapor pressure gradient resulting in dehumidification of the ambient air. A fraction of the desiccant solution is regenerated, initially passing through a liquid−liquid heat exchanger (state 2) where it is preheated (state 3) by the returning hot regenerated solution (state 5). The hot desiccant stream flows through an expansion valve (state 4) and enters a flash drum desorber. The flash drum unit receives heat from a low-grade heat source (e.g., solar heater, state 12) that facilitates desorption of water from the desiccant solution. It is noteworthy that due to the very high vapor pressure of the desiccant solution it does not evaporate. The reconcentrated hot solution (state 5) regains pressure by a barometric leg, and returns to the absorption cycle after passing through the liquid−liquid heat exchanger. The pure water vapor (state 7) enters the condenser, where the pressure is the saturation pressure at the condensation temperature. The latent heat of condensation is removed by a coolant (state 10 and 11), which is cooled by a refrigeration system external to the LDS system. The vacuum pump removes noncondensable gases that might be released from the desiccant solution, thus avoiding pressure buildup. The condensed water (state 8) regain atmospheric pressure by another barometric leg and are collected in a storage tank (state 9).

## MODEL OF THE LDS SUBSYSTEM

The operation of the LDS subsystem under various ambient conditions was modeled by ABSIM • a dedicated software that solves for the thermodynamic states of liquid-desiccant absorption systems and simulates their operation conditions.[22] Various liquid desiccants can be used for absorbing atmospheric moisture. In this study, we chose to use LiCl due to its suitable properties and chemical stability. Using ABSIM, we studied a range of possible ambient air temperatures (7−35 °C) and mixing ratios (0.006−0.024 $kg_w/kg_a$), and their effect on the LDS subsystem performance, assuming atmospheric pressure and applying 1 °C and 0.001 $kg_w/kg_a$ steps. Model parameters for which convergence for the whole range of input conditions was achieved were found by a trial-and-error procedure (see the Supporting Information, SI). Model results include the energy requirements of the condenser (states 10−11) and the desorber (states 12−13), which are assumed to be supplied by components external to the LDS vapor separation system. Since solar water heating is common, and as the coolant refrigeration can be achieved by various methods, these processes are not considered further in this study. For any ambient conditions, the model was examined for a range of cooling and heating stream properties, to determine the operation conditions that yield the highest water production rate (see the SI for further details). The liquid desiccant concentration and temperature were then inspected throughout the system (Figure 1) to ensure that the desiccant solution has not attain crystallization[23] (since ABSIM targets other applications and does not have this feature). Namely, while a highly concentrated desiccant solution is advantageous for efficient absorption of the water vapor from the air, if the concentration of the LiCl solution cross its solubility limit the salt will crystallize, clog the pipes and damage the system. The optimal operation conditions were selected such that the water production rate is maximized while still keeping a 2 °C safety margin from the crystallization boundary and a 1 °C margin from the ABSIM numerical convergence boundary.

## COMPARATIVE ANALYSIS

To assess the advantages of LDS-AMH systems, we compared their performance to that of conventional direct-cooling AMH systems. Whereas LDS-AMH systems operate using both thermal and electrical energy, conventional AMH systems operate using solely electrical energy. Hence, the comparison between the two systems is based on the assumption that the LDS-AMH system receives low-grade heat from a conventional solar heater. Namely, the comparison is performed between the nonsolar energy requirements of the LDS-AMH system (accounting for the latent heat of vapor condensation and for parasitic loses) and those of direct cooling systems. For LDS-AMH systems, only the latent heat of vapor condensation needs to be removed from the coolant before it is recirculated to the condenser. In contrast, for conventional direct-cooling systems the total heat interaction (latent heat of condensation + sensible cooling of the air) needs to be removed, with the latter calculated using the MHI.[18] Moreover, we compared the electrical work requirements (w) of the two systems under the assumption that they use refrigeration units with an identical coefficient of performance (COP = q/w). Although the COP depends on the temperature and increases with decreasing differences between the ambient air temperature and the condensation temperature, it is less sensitive than suggested by the ideal Carnot efficiency and is mainly determined by the equipment design parameters.[24] Thus, for the sake of simplicity, we assumed that the refrigeration units of both systems (LDS and direct cooling) have COP = 5.[19] In particular, the expected differences in the condensation temperatures (that would probably favor the LDS system in terms of COP) were neglected, making our analysis conservative.


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Both systems require electrical energy beyond the work supplied to the condenser. These extra energy requirements are termed here parasitic loses. However, the exact total parasitic loses cannot be determined without a detailed design of the system. It is expected that due to its complexity, the LDS-AMH system will bare higher parasitic loses than a direct cooling system, especially due to the larger airflow demand and the need to circulate the hot and cold streams as well as to operate a vacuum pump. The parasitic loses of an LDS module with air flow of 1 $kg_a$/s, desiccant flow of 0.15 kg/s, and heating and cooling streams of 0.5 kg/s (see SI) were estimated to range between 0.92 and up to 1.25 kW (based on technical specifications of LDS components[25] and on commercially off-the-shelf components). A detailed account of the estimated parasitic loses appears in the SI.

## RESULTS

Operational Model. The freshwater production rate of LDS-AMH systems depends on the ambient conditions, with the freshwater yield increasing with the ambient mixing ratio and decreasing with the ambient temperature. Figure 2a shows the expected water production rate for a range of ambient conditions. The results of the constrained optimization model, i.e., the temperatures of the hot stream that needs to be supplied to the desorber and of the cold stream that needs to be supplied to the condenser, are shown in Figure 2b,c, respectively. Model results reveal that the temperature of the hot stream should be higher for higher ambient moisture content (mixing ratio) conditions and that the lowest temperature of the cold stream is required for moderate mixing ratios and high relative humidity conditions. Yet, higher cold stream temperatures are sufficient for higher ambient mixing ratio conditions. This result stems from the divergence of ABSIM for high ambient temperatures and mixing ratios while disproportionately low cold stream temperatures are attempted. As expected, the heat interaction of the condenser is correlated with the water yield (with an only small effect of the condensation temperature) and equals the latent heat of condensation - the minimum heat interaction of a condensation process.

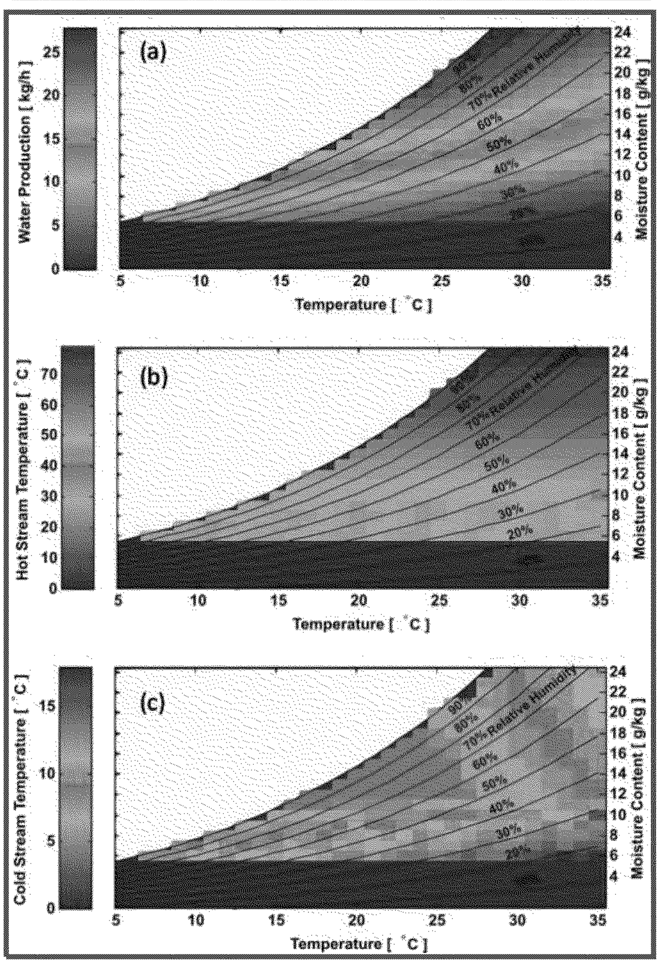


Figure 2. Results of the operational model for a range of ambient conditions. (a) Water production rate, (b) the hot-stream temperature at the inlet to the desorber, and (c) the coolant temperature at the inlet to the condenser.

Energy Costs. The heat interaction of the condenser in the LDS-AMH system was compared to the heat interaction of an electrical direct-cooling AMH system that cools the entire air bulk to 4 °C and produces freshwater at the same rate. For most of the investigated scenarios (ambient conditions), the heat interaction of the condenser of the LSD-AMH system is smaller by 10−13 kW than that of the direct-cooling AMH system, representing 40−90% saving. The actual electrical work of the systems depend on the COP of the refrigeration unit and on all the system parasitic losses (taken to be 1.25 kW, see SI). The specific energy requirement per freshwater production of the LDS-AMH system for a range of ambient conditions is presented in Figure 3 (range: 0.18−0.28 kWh/l). Significant increase in the specific energy requirement is evident if the system operates when the ambient relative humidity <30%.

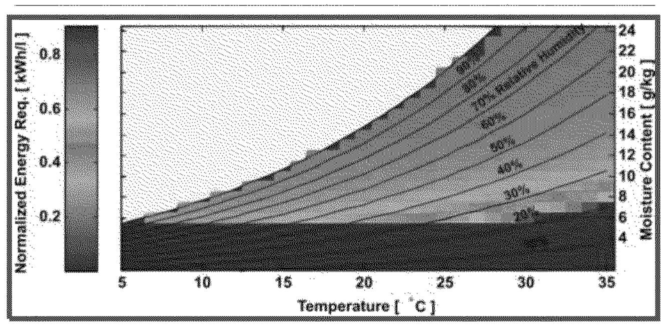


Figure 3. Electrical energy requirements of the LSD-AMH system for different ambient conditions.

Since the LDS-AMH system is more complex than conventional AMH systems and as parasitic losses are difficult to estimate, since they depend on the exact design of the system, we examined the effect of 50% surplus parasitic losses (1.88 kW), to see if inaccuracy in their estimation changes considerably our results. The results of this sensitivity test, normalized to the energy requirements per unit water production (kWh/l), are reported in Table 1.

## DISCUSSION

Active atmospheric moisture harvesting requires using the environment as a heat sink. The minimum amount of heat that has to be removed during the process is the latent heat of condensation. Conventional AMH systems use electromechanical refrigeration units to lower the temperature of the whole air bulk below its dew point and collect the excess water that condense from the supersaturated air. However, this method is


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Table 1. Performance of the LDS-AMH System (Model Results) and of Off-the-Shelf Direct-Cooling AMH Systems (According to the Manufacturers' Specifications)

| | | commercial AMH systems | | | | |
|---|---|---|---|---|---|---|
| | | Watergen GEN-350G | Watair CI-7500 | Watair CI-5000 | Watair AirJuicer 4010 | Skywater 300 |
| inlet air temperature | °C | 25 | 26.7 | 26.7 | 26.7 | 27.2 |
| inlet air relative humidity | % | 55 | 60 | 60 | 60 | 47 |
| energy requirement | kWh/l | 0.31 | 0.32 | 0.39 | 0.63 | 0.40 |
| | | computed LDS-AMH system results (1.25 kW parasitic losses) | | | | |
| energy requirement | kWh/l | 0.24 | 0.23 | 0.23 | 0.23 | 0.26 |
| energy saving | % | 21.8 | 29.7 | 42.3 | 64.3 | 35.7 |
| | | computed LDS-AMH system results (1.88 kW parasitic losses) | | | | |
| energy requirement | kWh/l | 0.29 | 0.27 | 0.27 | 0.27 | 0.31 |
| energy saving | % | 5.3 | 16.6 | 31.5 | 57.6 | 22.5 |

inefficient as it requires investment in cooling of noncondensable gases (dry air). This wasted energy can sum up to 40−90% of the total energy requirements of the process.[18,19] Energy savings can be obtained by separating the vapor from the dry air. A liquid desiccant separation system (LDS) has been proposed for this purpose, and its performance was studied numerically for a range of ambient conditions. Model results reveal that the temperature of the hot stream that ought to be supplied to the desorber should range between 50 and 80 °C, depending on the operation conditions. This stream can be obtained from a conventional solar heater. Depending on the ambient conditions, the condensation temperature can range from 4 °C and up to 15 °C. These temperatures can be maintained in the condenser using different refrigeration technologies. Figure 2a reveals that the LDS-AMH system can produce water for almost any ambient condition, yet the water yield depends on the ambient conditions due to the sensitivity of the liquid-desiccant absorption process to the ambient vapor pressure. However, the system's efficiency (i.e., the energy requirement per freshwater production) is less sensitive to the ambient air thermodynamic state (Figure 3). In general, for almost any ambient conditions the LDS-AMH system is expected to produce water for less than 0.3 kWh/l, and for the most favorable conditions the energy requirement is only 0.19 kWh/l. Operating the LDS-AMH system when the relative humidity is <30% is inefficient, since it has high energy demand per water production (Figure 3).

In general, the LDS-AMH system is expected to save 5−65% of the energy expenses of water production relative to off-the-shelf direct-cooling AMH systems (based on data obtained from manufacturers of standard AMH devices). In fact, even under the conservative parasitic losses scenario (50% higher than expected) the LDS-AMH system is more efficient by 5−58% (ambient conditions dependent) than commercial direct-cooling systems. Moreover, scaling up the LDS system to produce larger amounts of freshwater is possible simply by installing additional absorbing units around a single desorber-condenser core. Consequentially, the freshwater yield will increase proportionally with an only marginal increase in construction costs.

Another important advantage of the LDS-AMH system over direct-cooling AMH systems is the quality of the produced water. The chemical and physical quality of water produced by a direct electrical cooling AMH system is satisfactory, with low turbidity, neutral to acidic pH and very low salinity.[26] However, the microbial quality is of concern, since the condensate may be contaminated by airborne bacteria.[27] Filtration and disinfection processes are therefore required for domestic AMH use, and bare additional energetic cost of about 0.4 kWh/l.[28] In contrast, for an LDS-AMH system, the coil of the condenser does not come into contact with the ambient air but only with pure vapor that has been desorbed from the desiccant solution. While airborne particles may contaminate the desiccant solution, they are not volatile and will not be released from the solution in the desorber. Moreover, airborne bacteria will face an osmotic shock[29] by the extremely concentrated desiccant solution, which will result in plasmolysis of any nonhalophile bacteria (the osmotic pressure of the LiCl solution in contact with the ambient air in the absorber is expected to be about 145 MPa). Solid particles and plasmolysis residues can easily be filtered out of the desiccant solution, saving the need to install a filter at the ambient air inlet, and the energy to overcome the pressure drop it causes. However, LDS-AMH systems are more complex than conventional AMH systems and are therefore expected to bare higher capital costs. A detailed cost analysis of LDS-AMH systems is beyond the scope of this study but should consider the use of other liquid desiccants (e.g., $CaCl_2$ has similar properties to LiCl). Furthermore, construction of a LDS-AMH system must be justified economically, accounting for the saving in long-distance piping infrastructure of decentralized water production as well as for the need to use resistant materials due to the liquid desiccant corrosivity. Nonetheless, LDS-AMH technology seems to have great potential for supplying freshwater to remote populations living in favorable climate conditions.

## ASSOCIATED CONTENT

* Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.6b01280.

Operational parameters of the simulated LDS system, demonstrates the constrained optimization process used for determining the working point at any ambient air condition, provides a detailed account of the parasitic losses, and presents the increase in the normalized energy requirements that result from accounting for 50% surplus parasitic losses (PDF)

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Notes

The authors declare no competing financial interest.

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